General purpose Equations of State

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Overview

- Update on general purpose EOS
- Thermal properties of nucleonic models
- Thermal properties of models with exotic d.o.f.

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Update on General purpose EOS

- from 1991 to 2010 only two EOS:

  (1) Lattimer & Swesty (LS) [NPA 535, 331 (1991)];
  (2) Shen, Toki, Oyamatsu & Sumiyoshi (STOS) [NPA 637, 435 (1998)]

- "finite-T" EOS have been "built" by Γ-law [Bauswein+ (2010)];

- starting with 2010 the situation improved a lot, e.g., on CompOSE*
  - more than 100 EOS are now available,
  - more than 40 EOS account for Λ, Y, Δ, π, K; different blends; hadron to quark phase trans.
  - effective interactions: Skyrme, Covariant Density Functionals, ab-initio;
  - various NM properties, i.e. n_{sat}, E_{sat}, K_{sat}, J_{sym}, L_{sym}, K_{sym}, m_{eff}

- simulations of CCSN, BNS, stellar BH formation; effect of heavy baryons and a hadron to quark phase trans.; for non-rel. EOS $m_{rmeff;L}$ impacts the evolution [Yasin+, PRL (2020)] [Schneider+, ApJ (2020)] [Schneider+, ApJ (2020)]

- **Our purpose:** Systematic investigation of thermal effects

* `https://compose.obspm.fr`

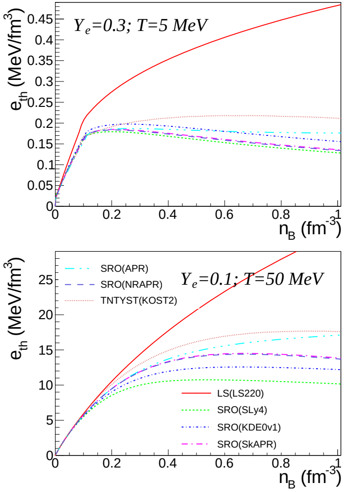
Nucleonic models

- 13 models
- 7 non-relativistic: SRO(APR), TNTYST(KOST2), LS(220), SRO(SLy4), SRO(KDE0v1), SRO(SkAPR), SRO(NRAPR),
  red: variational; blue: Skyrme-like
- 6 CDFT: HS(DD2), HS(IUF), SFH(SFHo), SFH(SFHx), SNSH(TM1e), SHO(FSU2)
- $L_{sym} = 58.7 \pm 28.1$ MeV; $K_{sat} = 230 \pm 40$ MeV,
- $1.94 \leq M_{max}/M_{\odot} \leq 2.21$
- models are available on `CompOSE`*

* `https://compose.obspm.fr/`
format suitable for input in numerical simulations

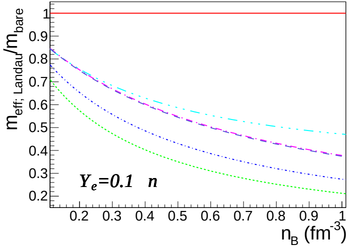
Non-relativistic models (I): thermal energy

$e_{\rm th} = e(n_B, Y_e, T) - e(n_B, Y_e, 0)$



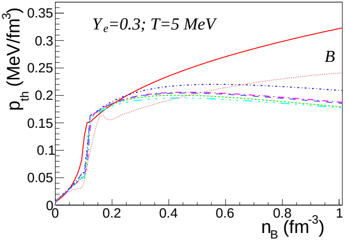
- low n_B, high T: ideal gas
  $e_{\rm th} = \alpha T$, $\lim_{n_B \to 0} e_{\rm th} \to 0$; no EOS-dep.;
- low n_B, low T: matter in clusterized; dependence on eff. int. and NSE
- high n_B: strong n_B-, T, EOS-dep.

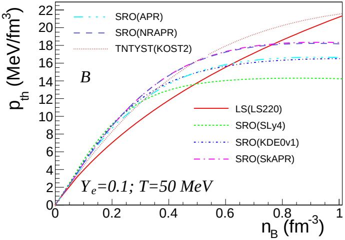
- models with large $m_{\rm eff;L}$ → large $e_{\rm th}$
  [Constantinou+, PRC (2014); PRC (2015)]



Non-relativistic models (I): thermal pressure

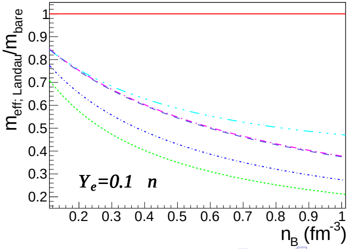
$p_{\rm th} = p(n_B, Y_e, T) - p(n_B, Y_e, 0)$





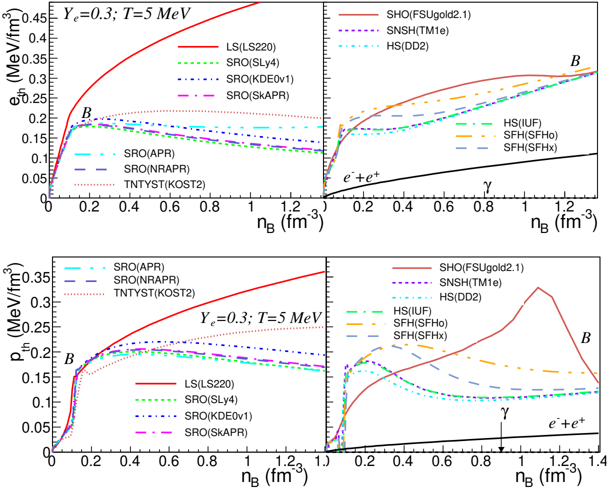
- low n_B, high T: ideal gas
  $p_{\rm th} = \alpha T$, $\lim_{n_B \to 0} p_{\rm th} \to 0$; no EOS-dep.;
- low n_B, low T: matter in clusterized; dependence on eff. int. and NSE
- high n_B: strong n_B-, T, EOS-dep.

- $p_{\rm th}$ depends on $m_{\rm eff;L}$, $dm_{\rm eff;L}/dn_B$ [Constantinou+, PRC (2014); PRC (2015)]



Theoretical framework dep. (I): $e_{\rm th}$, $p_{\rm th}$

non-rel. models RMF models



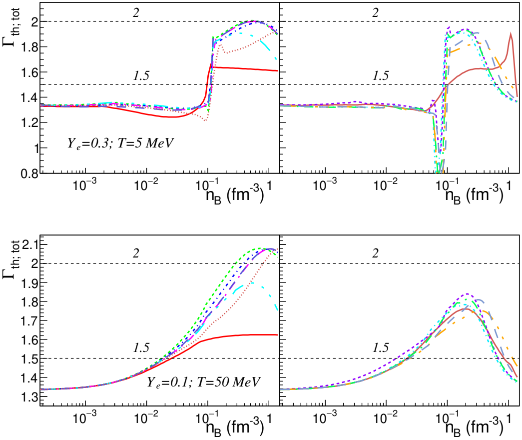
qualitative differences

[Raduta+, EPJA (2021)]

$$\epsilon(k) = k^2/2m_L^* + V(n) \qquad \epsilon(k) = \sqrt{k^2 + m_D^{*2}(T)} + \Sigma_V;$$

Thermal index $\Gamma_{\rm th} = 1 + p_{\rm th}/e_{\rm th}$

non-rel. models RMF models



low n_B: $\Gamma_{\rm th} < 1.5$, no EOS-dep.

high n_B: n_B-, T- and EOS-dep.
non-rel.: $\Gamma_{th} > 2$
RMF: $\Gamma_{th} < 1.5$

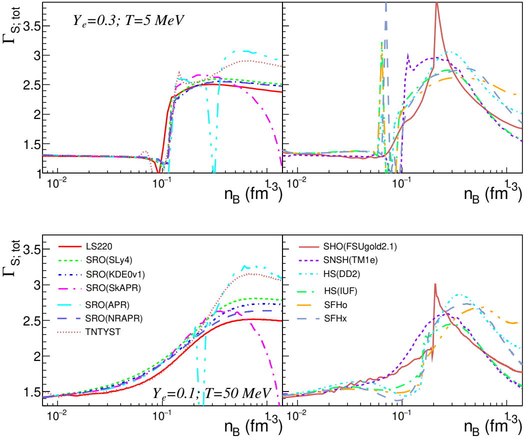
Γ-law is a crude approx.

$P(n_B, e) = P_{\rm cold}(n_B) + (\Gamma_{\rm th} - 1) e_{\rm th}(n_B)$

[Raduta+, EPJA (2021)]

Adiabatic index Γ_S

$\Gamma_S = (\partial \ln P/\partial \ln n_B)|_S =$
$C_P/C_V \cdot n_B/P \cdot (\partial P/\partial n_B)|_T$

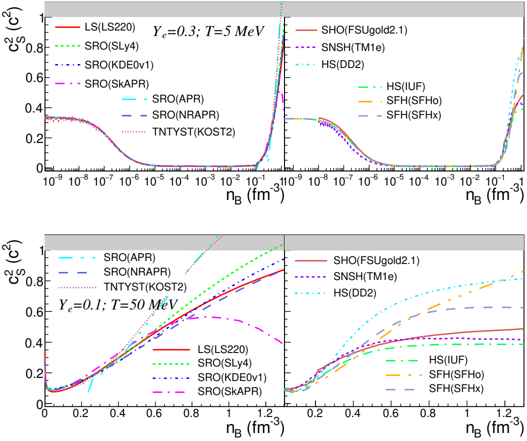


[Raduta+, EPJA (2021)]

- $\lim_{n_B \to 0} \Gamma_S \to 1.5$
- high n_B: Γ_S decreases
- for NSE models: irregularities at $n_{sat}/2$ for $T < T_C$
- for $T < T_C$ and $n_B < n_t$, $\Gamma_S \neq 0$
- APR: π condensed phase at $1.5 n_{sat}$
- strong EOS- and n_B dep.

Speed of sound c_s^2

$$c_s^2 = (dP/de)|_{S,A,Y_e} = \Gamma_S P/(e+P)$$



[Raduta+, EPJA (2021)]

- strong n_B, T and EOS-dep.
- at $T = 5$ MeV, 10^{-5} fm$^{-3} \lesssim n_B \lesssim n_t$: $c_s^2 \neq 0$: quenching of the transition or technicalities
- APR: π condensed phase at 0.2 fm^{-3}
- except SkAPR, for non-rel. models: c_s^2 increases with n_B
- for most CDFT models: c_s^2 saturates

Models with exotica

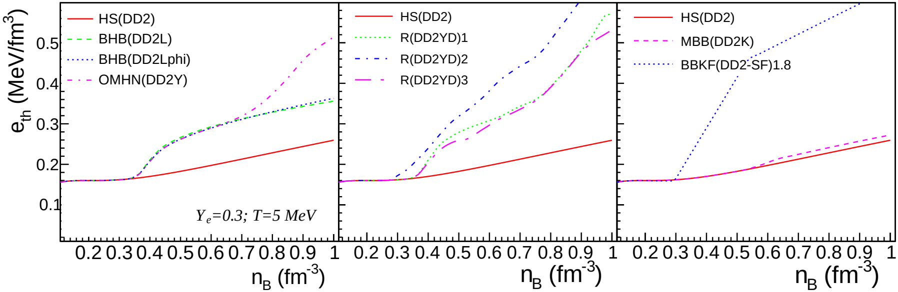
- 8 models based on DD2:
  BHB(DD2L), BHB(DD2Lphi),
  OMHN(DD2Y),
  MBB(DD2K),
  R(DD2YD)1 ($U_{\Delta}^{(N)} = -83$ MeV), R(DD2YD)2 ($U_{\Delta}^{(N)} = -124$ MeV),
  R(DD2YD)3 ($U_{\Delta}^{(N)} = -57$ MeV) [Raduta, EPJA (2022)],
  BBKF(DD2-SF)1.8

- models are available on CompOSE*

* https://compose.obspm.fr/

Thermal energy

$e_{th} = e(n_B, Y_e, T) - e(n_B, Y_e, 0)$



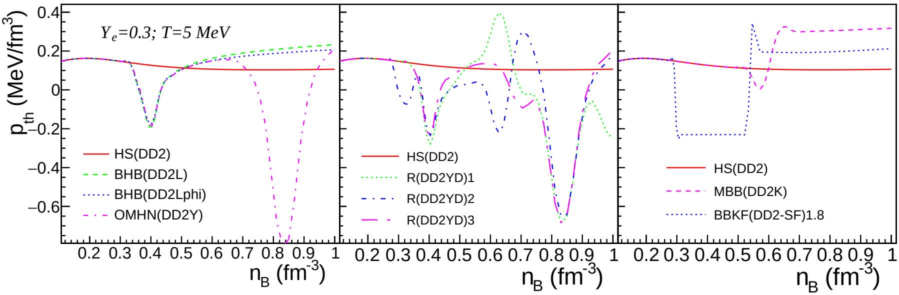
[Raduta, EPJA (2022)]

- $e_{\rm th}$ increases with n_B and T
- the larger the number of particle d.o.f. the larger $e_{\rm th}$

∘ $e_{\rm th}^{R(DD2YD)} > e_{\rm th}^{OMHN(DD2Y)} > e_{\rm th}^{BHB(DD2L)} > e_{\rm th}^{HS(DD2)}$

Thermal pressure

$p_{th} = p(n_B, Y_e, T) - p(n_B, Y_e, 0)$

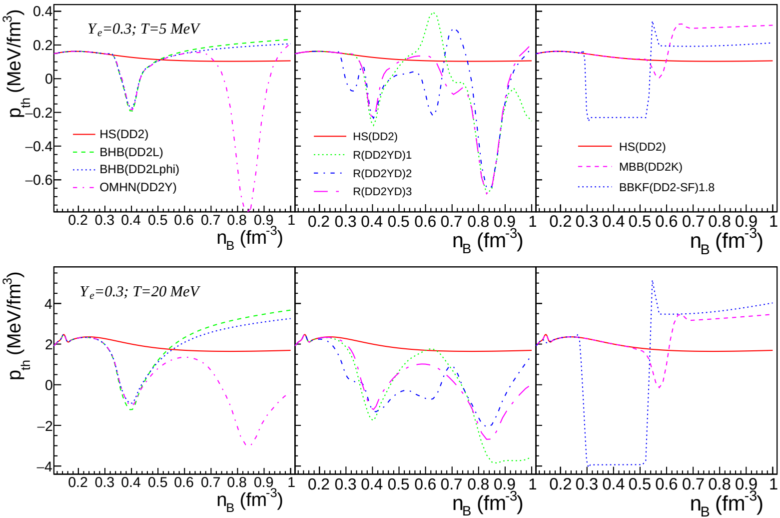


[Raduta, EPJA (2022)]

- nucleation of exotic d.o.f. diminishes $p_{\rm th}$
- under specific conditions $p_{\rm th} < 0$
- overall a strong n_B- and EOS- dependence; also T-dependence
- $p_{\rm th}$=const. in the coex. phase for (approximate) Maxwell construction; $p_{\rm th} \neq$const. if the hadron-quark phase trans. is done following Glendenning

Thermal pressure

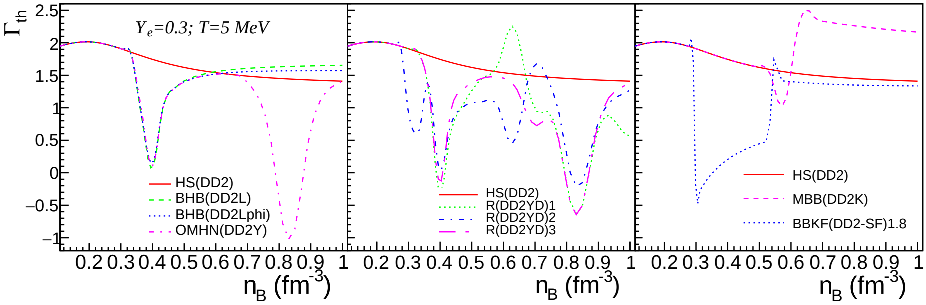
$$p_{th} = p(n_B, Y_e, T) - p(n_B, Y_e, 0)$$



- also T-dependence

[Raduta, EPJA (2022)]

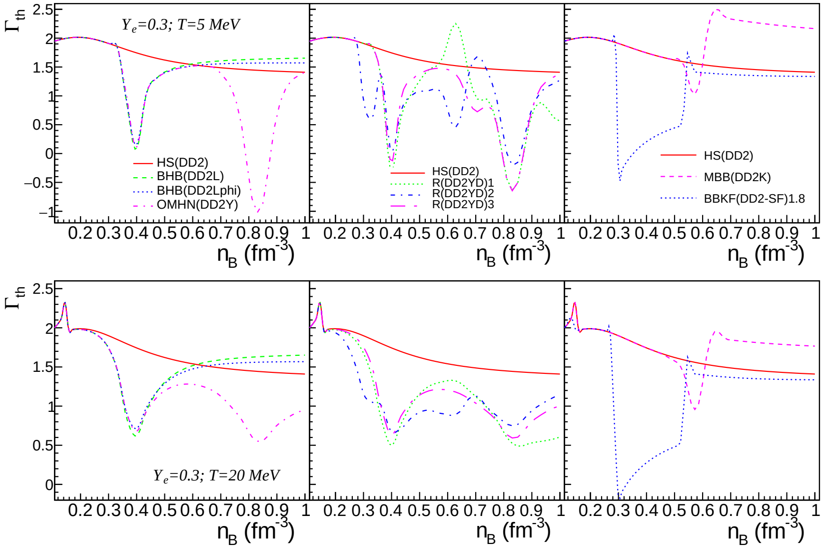
Thermal index $\Gamma_{th} = 1 + p_{th}/e_{th}$



[Raduta, EPJA (2022)]

- strong n_B- and EOS- dependence
- minima are related to the onset of new species
- $\Gamma_{th} < 0$
- for (approx.) Maxwell construction: Γ_{th} increases in the phase coex.
- $\Gamma_{th} < 1.5$ (the low limit of the Γ-law);
  use of Γ-law is inappropriate for models with exotica

Thermal index $\Gamma_{th} = 1 + p_{th}/e_{th}$



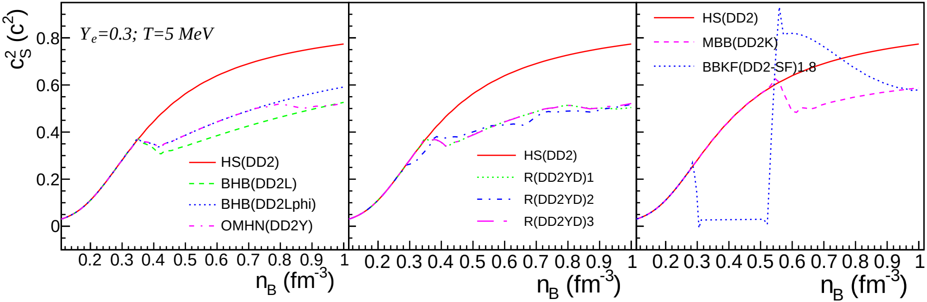
- also T-dependence

[Raduta, EPJA (2022)]

Speed of sound: $c_S^2 = dP/de|_{S,A,Y_Q}$

$c_S^2 = \Gamma_S P/(e+P)$

$\Gamma_S = (\partial \ln P/\partial \ln n_B)_S = (C_P/C_V)(n_B/P)(\partial P/\partial n_B)_T$



[Raduta, EPJA (2022)]

- strong n_B- and EOS- dependence;
- $c_S^2 = 0$ only for Maxwell treatment of phase coex.
- c_S^2 decreasing with n_B after the onset of a new species

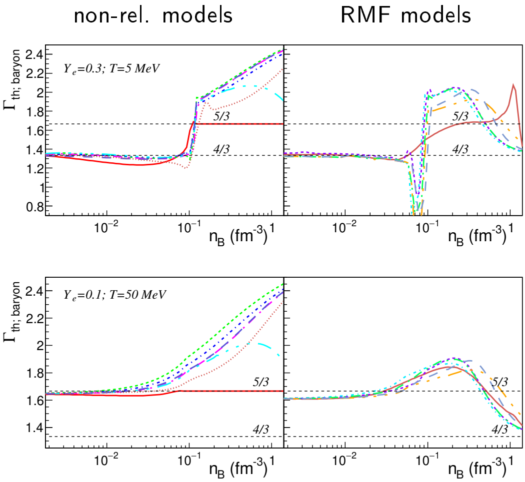
Conclusions

- we have reviewed thermal prop. of nucleonic EOS
  - non-rel. and relativistic models manifest different features
  - the role of single particle energies; Landau versus Dirac effective masses
  - $m_L^*(n_B)$, $dm_L^*(n_B)/dn_B$ affect all thermal properties

- Γ-law is proven not to provide a reliable solution

- we have reviewed thermal prop. of models with exotica
  - $e_{\rm th}$, $p_{\rm th}$, $\Gamma_{\rm th}$, c_S^2 shown to have strong n_B- and EOS-dependence; for exotic d.o.f. $p_{\rm th}, \Gamma_{\rm th} < 0$ at low T

Thermal index $\Gamma_{th} = 1 + p_{th}/e_{th}$: baryonic sector



[Raduta+, EPJA (2021)]

low n_B and high T:
$\Gamma_{th} \to 5/3$, ideal gas

RMF at high n_B:
$\Gamma_{th} \to 4/3$, ultra-rel. gas

strong n_B- and EOS-dep.

non-rel. and RMF qualitatively diff.